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DECONTAMINATION OF PICKERING NGS 'A'
SPENT FUEL STORAGE BASKETS -
AN ENGINEERING STUDY

Report No 86-285-K

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Chemical Research Department

ABSTRACT

The engineering requirements for decontaminating stainless steel PNGS "A" spent fuel storage baskets using a dilute solution of nitric and hydrofluoric acids are considered. A soak tank with associated purification, vapour handling and auxiliary systems is proposed. Materials for constructing the facility were identified and experimentally evaluated. The feasibility of regenerating spent decontamination solutions using a high temperature cation exchange resin, Amberlite 200, was investigated. It is concluded that regenerative HNO_3/HF solution decontamination of the stainless steel is technically feasible and would result in a relatively small volume of radioactive ion exchange waste.

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EXECUTIVE SUMMARY

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SPENT FUEL STORAGE BASKETS - AN ENGINEERING STUDY

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The final phase of a research program to specify and engineer a decontamination process for obsolete stainless steel spent fuel storage baskets from the irradiated fuel bay of Pickering NGS "A" is described. In the first phase, the type and level of radioactive contamination on their surfaces were characterized. Subsequently, decontamination testing led to the development of a regenerative process involving the use of a dilute solution of nitric (0.5-1.0 wt%) and hydrofluoric (0.05 wt%) acids. The overall objective of the program is the disposal as scrap of the decontaminated stainless steel.

The engineering requirements for the proposed decontamination are considered in the present study. In this regard, extensive discussions were held with contacts in the metal finishing industry where mixtures of nitric and hydrofluoric acids are routinely used at significantly higher concentrations to pickle and finish stainless steel.

The proposed decontamination facility consists of a soak tank with associated purification, vapour handling and auxiliary systems. Materials for constructing the facility were identified and experimentally evaluated. The feasibility of regenerating spent decontamination solutions using a high temperature cation exchange resin, Amberlite 200, was investigated. It is concluded that regenerative HNO_3/HF solution decontamination of the stainless steel is technically feasible and would result in a relatively small volume of radioactive ion exchange resin waste. Disposal of the acid solution which is expected to be a once-only occurrence at the end of the complete decontamination was also addressed.

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An economic evaluation of the proposed decontamination should consider the benefits of developing an in-house capability to effect large scale decommissioning-type decontaminations of metallic wastes in general. It is recommended that the detailed engineering and construction of the decontamination facility should involve the participation of metal finishing consultants and draw upon the considerable expertise in the stainless steel pickling industry.



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To Mr. R.T. Popple
Manager
Radioactivity Management
and Environmental Protection Department

DECONTAMINATION OF PICKERING NGS 'A' SPENT FUEL STORAGE
BASKETS - AN ENGINEERING STUDY

1.0 INTRODUCTION AND BACKGROUND

The replacement of obsolete stainless steel (SS-304) spent fuel storage baskets (SFSB) from the irradiated fuel bays of Pickering NGS 'A' will generate a large amount (about 200 tons) of radioactive waste. Considerable savings in storage costs would be realized if the baskets could be decontaminated and disposed of as metal scrap. Nuclear Generation Division has the option of applying to the Atomic Energy Control Board (AECB) for permission to dispose of the decontaminated wastes by conventional methods.

Residual radioactivity levels after decontamination should be sufficiently low to pose no radiation hazard to the public and the environment. Based on past regulatory decisions, any residual beta-gamma (β, γ) contamination should be below $1 \mu\text{Ci}/\text{m}^2$ averaged over a 0.03 m^2 surface. Due to the large amount of material involved, it is felt that a target level one-tenth of the above ($0.1 \mu\text{Ci}/\text{m}^2$) may expedite regulatory approval/1/. Due to the high toxicity of most alpha emitters, any residual alpha contamination should be very low. In the US, the unrestricted release limits for transuranics is $4.5 \text{ nCi}/\text{m}^2$.

An earlier report/2/ described the first phase of work undertaken at the request of Radioactivity Management and Environmental Protection (RMEP) Department to specify a process for decontamination of the obsolete Pickering SFSBs. Characterization of the radioactive contamination on the basket surfaces indicated a (β, γ) surface activity of $10\text{-}30 \mu\text{Ci}/\text{m}^2$ largely due to Cs-137, Co-60 and Sb-125. Alpha activity was considerably smaller ($7 \text{ nCi}/\text{m}^2$) and due to plutonium isotopes, Am-241 and Cm-244. The contamination was found to penetrate the thin (in the order of $100 \text{ \AA}$) surface oxide layer into the base metal to a depth of a few microns.

Preliminary decontamination testing indicated that a reagent with the composition 10% nitric acid + 0.3% hydrofluoric acid + 1.7% aluminum nitrate was effective in reducing the contamination level below $0.1 \mu\text{Ci}/\text{m}^2$. A dilute two step process consisting of an alkaline permanganate pretreatment followed by exposure to a mixture of organic acids (EDTA, citric acid and oxalic acid) also appeared promising.

Further evaluation/3/ indicated the nitric and hydrofluoric acids based reagent to be the most effective. Its optimum concentration was determined to be (0.5 - 1.0) wt% nitric acid + 0.05 wt% hydrofluoric acid. Application of this reagent to basket surfaces (trays) for 1 h resulted in a metal removal exceeding $1 \mu\text{m}$ and a residual contamination below the target limit of $0.1 \mu\text{Ci}/\text{m}^2$. Preliminary investigations using IRN-77, a strong acid cation exchanger, indicated that the acid solutions could be continuously regenerated during a decontamination. It was recommended that the reagent developed be further evaluated on a pilot plant scale before full scale field trials are attempted. This would require selection of materials suitable for construction of a decontamination facility. The facility would include ion exchange provisions for continuous regeneration of the solution during decontamination.

Mixtures of nitric and hydrofluoric acids at concentrations much higher than those recommended above for the decontamination are routinely used by the metal finishing industry to pickle and finish stainless steels/4-8/. For this reason and due to the urgent¹ need to choose between two competing treatment options for the SFSBs, namely 1) disposal following decontamination and 2) compaction and storage, RMEP felt that an engineering study to determine field requirements for the proposed decontamination would be more appropriate than a pilot scale investigation. The engineering study would be essentially conceptual in scope, and include materials evaluation and selection along with further investigations on regeneration of spent solutions using ion-exchange. Cost comparisons could then be made with the alternative to compact and store the radioactive waste.

The work outlined above is presented in the following sections. However, prior to a discussion of the subject, a brief review of the dissolution behaviour of SS304 in a pickling acid environment is given. The latter is based on a recently published work/4/ and sheds some light on the process chemistry involved during the decontamination. Also, the industrial practice in stainless steel

¹ Due to difficulty in sectioning and hence effecting a volume reduction, PNGS "A" has begun transferring the baskets intact to BNPDS for storage.

pickling is briefly discussed to afford the decontamination process operator a measure of confidence in the handling of the hazardous acids involved.

2.0 DISSOLUTION BEHAVIOUR OF SS304 IN HNO₃/HF MIXTURES

A detailed study of the dissolution behaviour of SS304 in an HNO₃/HF acid pickling environment was recently reported by Covino et al/4/. This appears to be the first study of its kind. Conditions investigated were: time 0-90 min, temperature 30-90°C, HNO₃ 0.8-3.5 M (5-22 wt%), HF 0.5-2.6 M (1-5.2 wt%) and 0-0.21 M dissolved Fe, Cr and Ni (as nitrates). Solutions were deaerated prior to sample exposure.

Measured dissolution rates were constant over the 90 min exposure period indicating no effect of dissolution products buildup. However, when metals (as nitrates) at relatively high concentrations (0.1 - 0.2 M) were initially present in the solution, the rate increased within a short initial period to a steady state level which was lower than in the case with no added metal.

The steady state rate with or without added metal increased linearly with HF concentration. Variation of the rate with HNO₃ concentration (reported only for the case without added metal) was more complex: the rate exhibited a maximum at 0.4-1.5 M HNO₃ depending on the temperature and concentration of HF, decreasing eventually to a relatively constant value. This may be due to competition between metal oxidation and NO formation which occurs to a greater extent at higher HNO₃ concentration.

The activation energy was not significantly affected by HF and added metal concentrations but passed through a minimum at 1.3 M HNO₃.

Among the dissolved metals, Fe was the most effective in reducing the dissolution rate (the steady state rate decreased linearly with increasing concentration) followed by Cr while Ni had no effect. This inhibiting effect was suggested as due to the specific cation's ability to tie up available F⁻ ions (stability constants are in the order $\text{FeF}^{+2} > \text{CrF}^{+2} > \text{NiF}^{+}$ with that for NiF^{+} being comparable to the constant for the most prevalent ionized fluorine species HF_2^{-}).

Auger electron and X-ray photoelectron spectroscopies of solution-exposed stainless steel samples revealed the presence of an adherent surface film (less than a monolayer coverage) of fluorine possibly as FeF_3 and CrF_3 . Chromium enrichment on the surface was also noted.

Despite Cr enrichment on the surface, the authors suggest based on the magnitude of measured activation energies that the dissolution of SS304 in HNO_3/HF media is not inhibited by a passive surface film but is controlled by processes occurring in the bulk solution or at the film-solution interface.

Most of the effects reported by Covino et al/4/ have also been observed in the SFSB decontamination studies/3/. Due to the two-level factorial design methodology adopted in the experimentation, the maximum with respect to HNO_3 concentration was not observed but may also be a feature of the dissolution rate in the decontamination. Metal losses in the decontamination were lower (for comparable cases) by factors of up to 4 compared with estimations from the results of Covino and co-workers. This is presumably due to the adverse effect of metal buildup on the dissolution rate during long (4 h) exposures although other factors such as the degree of cold work may also be instrumental.

3.0 PICKLING OF STAINLESS STEEL - INDUSTRIAL PRACTICE

Considerable expertise in the handling of nitric and hydrofluoric acids for pickling of stainless steels resides with steelmakers, among others, Allegheny Ludlum Steel Company and Crucible Materials Corporation in the US and Atlas Steel in Canada. A brief description of their facilities and operating practice is given below. It is based on contacts made at the three locations and a field trip to Atlas Steel's facilities in Tracy, Quebec.

Allegheny Ludlum/5/ perform their pickling operations in uncovered 10,000 gallon (60' long x 8' wide x 2-3' deep) polypropylene-lined carbon steel tanks using 6-10% HNO_3 + 1-2% HF at 60°C. The solution is agitated using plastic-lined recirculating pumps and warmed with external Teflon heat exchangers. Nitrogen oxide fumes from the tank are converted into N_2 and O_2 gases using a proprietary water scrub process. Make-up water is added to replenish evaporation losses. Acid make-up is based on periodic concentration monitoring. The tank solution is regenerated (at a flow rate of 4000 gallons/day) using Toronto-based Eco-Tec's RECOFLO ion exchange acid purification system².

Crucible/7/ operate batch pickling facilities with capacities

² The heart of the purification system is a bed of special sorption resin. During the absorption step, spent acid flows up through the resin bed resulting in acid sorption and rejection of dissolved metal salts in the mildly acidic effluent. In the subsequent step, water flowing counter-currently is used to desorb the acid from the resin. The two steps operating in rapid alternating sequence effect a continuous regeneration of the acid stream/6/.

ranging between 3000 and 7000 gallons using solutions similar in composition to those described above. No agitation is provided for other than that caused by movement of the metal work. Solutions are warmed using Teflon heat exchangers or by direct steam sparging although the latter results in acid dilution. A push/pull system for vapour control is used on older open top tanks while scrubbers are employed on their newer covered tanks. An Eco-Tec acid purification system is being considered; at present, however, spent solutions containing 3-4% metal are treated with lime for disposal at a landfill.

The pickling facilities at the Atlas Steel plant in Tracy/8/ are operated similarly to those of the other two. The tanks have a multilayered construction, namely, a carbon steel shell lined with butyl rubber which in turn is separated from the solution exposed layer of carbon bricks by a sheet of Teflon. The tanks are covered on top and maintained at a slightly negative pressure with the vapours being drawn through a scrubber. The solution is agitated by air sparging. A clearance of about one foot is maintained above the liquid level in the tank. There is no provision for continuous regeneration of the acid solutions; spent acids are treated with lime and disposed of at a landfill. Make-up acids are gravity fed (from holding tanks located outside the plant) to minimize usage of valves and fittings. Occasionally, pickled sheet metal rolls with a poor finish are reprocessed through another pickling cycle. In this case, acid attack on the predominantly oxide-free metal surface causes significant evolution of hydrogen; its concentration above the liquid is, however, always well below hazard limits.

Discussions with Allegheny, Crucible and Atlas Steel elicited a favourable response with respect to the technical feasibility of the SFSB decontamination. Proper choice of materials was emphasized to ensure success.

4.0 SFSB DECONTAMINATION - PROCESS CONDITIONS AND SCALE-UP REQUIREMENTS

On the basis of earlier/3/ decontamination experience with SFSB tray surfaces (see Figure 1), optimum conditions for process application were suggested as:

$\text{CHNO}_3 = (0.5-1.0) \text{ wt\%}$

$\text{CHF} = 0.05 \text{ wt\%}$

$t = 1 \text{ h}$

$T = 95^\circ\text{C}$

Metal surface/solution volume = $(10-20) \text{ m}^{-1}$

Dissolved metal concentration not to exceed³ 60 ppm, and

Exposure under deaerated and well agitated solution conditions.

³ Re-use of solutions containing a metal concentration in excess of 60 ppm caused erratic reagent performance/3/.

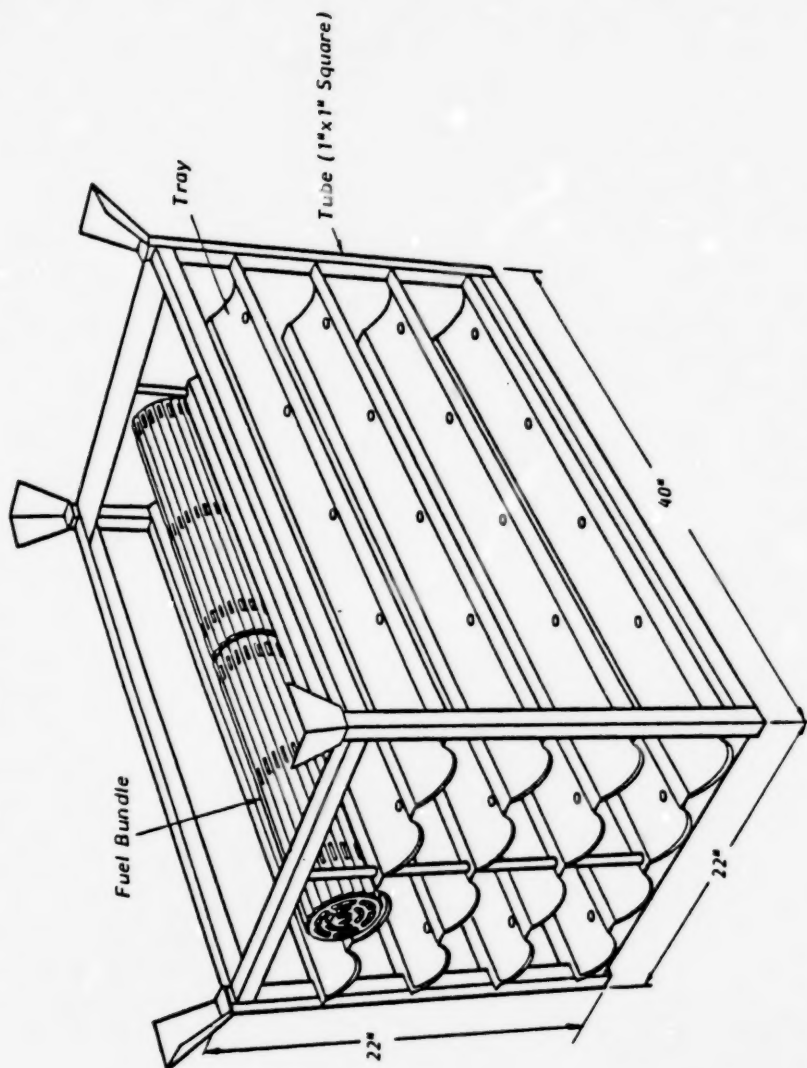


FIGURE 1
PICKERING GS FUEL STORAGE BASKET

Under the above conditions, the metal removal rate from the SFSB tube surfaces was lower than from its tray surfaces; however, the residual contamination on the tube surfaces was within the target level of $0.1 \mu\text{Ci}/\text{m}^2$. Although the activity remaining on decontaminated SFSB weld sections was generally about 5 times higher, their small contribution to the overall surface implies that intact decontamination of the SFSB would yield an acceptable overall residual contamination level.

In addition to the SFSBs, the associated cage and base plate assemblies also have to be decontaminated. The structures are shown in Figures 2 and 3. Approximately 2250 SFSBs, 700 fuel racks and 700 base plates require processing/9/. To minimize sectioning, the proposed decontamination facility should accommodate baskets and base plates intact with the cage assemblies appropriately sectioned to fit. The estimated surface area per SFSB or base plate is $6.5 \text{ m}^2/9/$. The SFSB and base plate weigh⁴ 73 and 150 kg, respectively.

5.0 SFSB DECONTAMINATION - CONCEPTUAL DESIGN OPTIONS

Two conceptual design options for a decontamination facility were considered, namely 1) an automatic Parts Washer concept, 2) a soak tank system. Both are briefly discussed below.

There are two Parts Washers at Pickering NGS. One, manufactured by Quinel International Ltd (now defunct), is used for routine decontamination of parts and tools. The second, made by Proceco Industrial Machinery Ltd, is specific to the needs of the LSFCRP⁵ Annex. These semi-automatic washers feature a recirculating spray system with a three stage wash, rinse and dry cycle. The machines are self-contained with their own heating and exhaust systems.

A Parts Washer concept is attractive for decontaminating SFSBs and associated structures for two reasons: 1) once the washer is loaded, the need to physically transport the work object between stages is avoided, and 2) impingement of the acid spray on the work would probably enhance its rate of decontamination. Accordingly, Proceco and others were contacted regarding the feasibility of a custom built facility to decontaminate the SFSBs. Due to the specialized material requirements, elevated temperature service and desirability of a deaerated environment, the consensus was that a Parts Washer concept would be prohibitively expensive to implement. This option was, therefore, not pursued further.

⁴ Weight of the base plate was calculated from its estimated surface area assuming a metal thickness of 0.3 cm and a density of 8 g/cc. It should be independently confirmed.

⁵ Large Scale Fuel Channel Replacement Program.

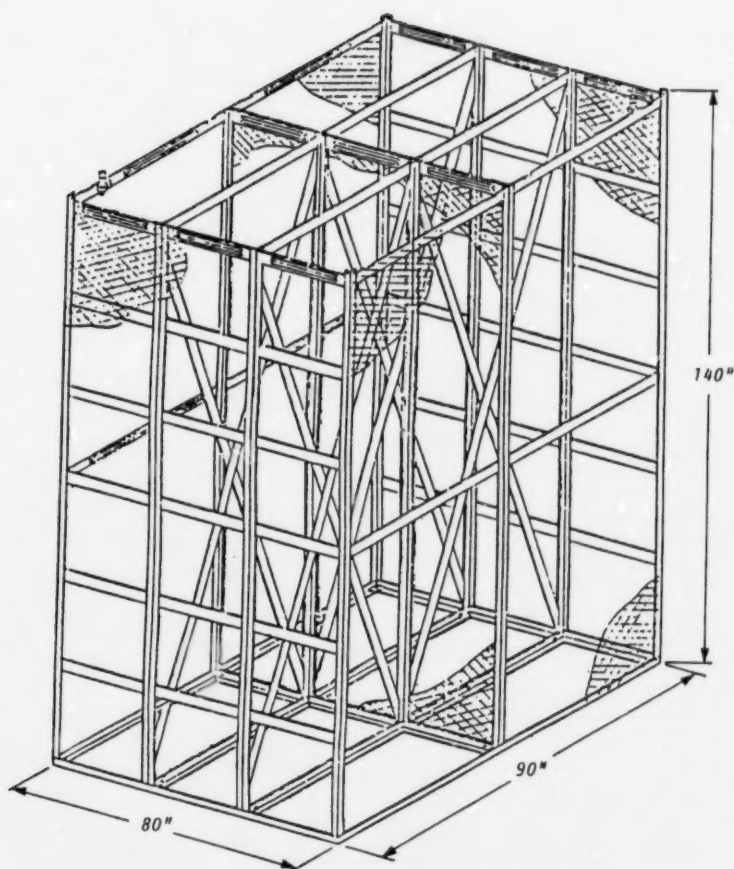


FIGURE 2
PICKERING GS SPENT FUEL STORAGE CAGE ASSEMBLY

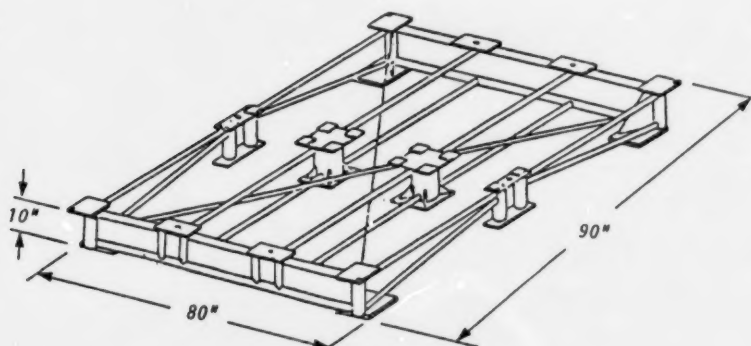


FIGURE 3
PICKERING GS SPENT FUEL STORAGE BASE ASSEMBLY

The second option is a soak tank system similar in principle to that employed in acid pickling of stainless steels. In this option, the SFSBs and associated structures are immersed for the requisite duration in solution contained in a tank equipped with its own heating, vapour handling and purification systems. The structures are subsequently retrieved from the tank and placed on a drain table. The drained acid is returned to the soak tank. The structures are then advanced to a rinse booth and sprayed with fresh tap water. The rinse water, collected in a holding tank, is sampled periodically and released due to its expectedly negligible acid, metal and radioisotope concentrations. Rinsed structures thereafter pass over a drying table and into transfer containers. A monorail is used to transport structures between the various processing stations.

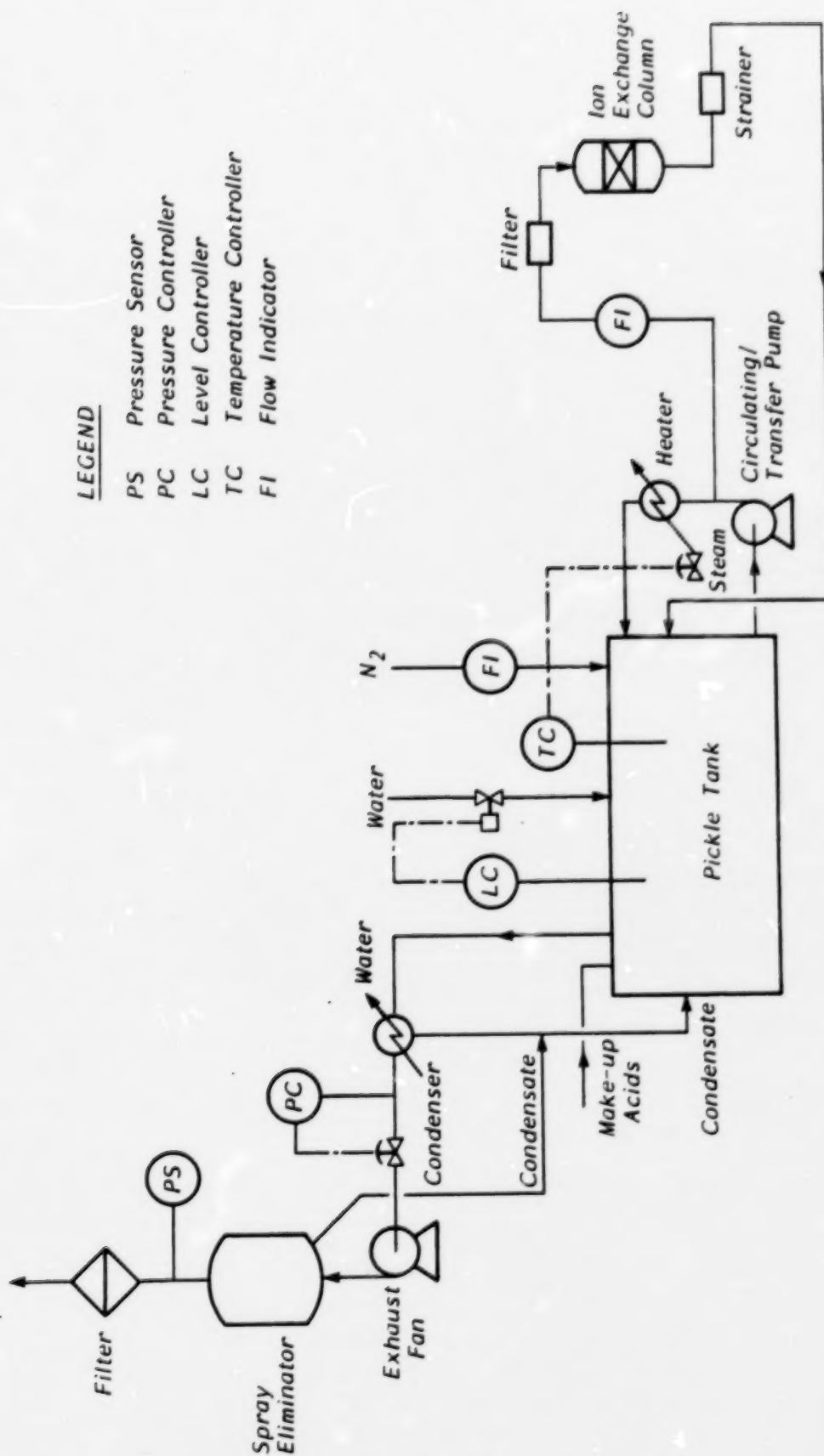
In view of the well established infra-structure serving metal finishers in general, the feasibility of the second option appeared obvious. The next section examines the soak tank and associated systems in some detail.

6.0 THE SOAK TANK AND ASSOCIATED SYSTEMS

The Metal Finishing/10/ guidebook is a useful source for preliminary plant design. However, the information contained therein is rather general and not specifically related to HNO_3/HF acid systems. A consulting firm, Ledge Engineering⁶, was therefore requested to propose a preliminary flow sheet, material choices and a cost estimate for a facility to decontaminate the SFSB radioactive waste. A tank size of cross-section 11' x 10' and depth 4' was specified. This could accommodate six SFSBs intact or a base assembly on an appropriate supporting rack.

The flow sheet proposed by Ledge, suitably amended, is shown in Figure 4. The tank is equipped with a nitrogen sparger which serves as the primary means for liquid agitation (based on 0.4 cfm/ft², the gas flow rate was estimated to be 40 cfm at 3-5 psi/10'), make-up water supply (over 500 lb/h would be required), make-up acid supply, vapour handling system, purification system and a heat exchanger. Vapours (principally steam and acids) and gases (principally N_2 , NO_x and H_2) pass through a condenser; the condensed vapours are returned to the tank, while the non-condensables are extracted by a fan and exit through a spray eliminator and an absolute filter. The purification system consists of filters and ion exchange columns. It is operated at system temperature when required (see Section 8). The external

⁶ Recommended by Eco-Tec and Atlas Steel.



LEGEND

- PS Pressure Sensor
- PC Pressure Controller
- LC Level Controller
- TC Temperature Controller
- FI Flow Indicator

FIGURE 4
PRELIMINARY FLOW SHEET FOR DECONTAMINATION OF SPENT FUEL STORAGE BASKETS

heat exchanger utilizes steam at 276 kPa⁷. Jetting of solution from heater outlet provides additional agitation of liquid in the tank.

The tank has a hinged top which rests during operation in a double water seal that seals up to a pressure of ± 3 " water column (the exhaust fan keeps the tank pressure within this range).

The supporting rack is equipped with lifting lugs which protrude above the liquid level so that hoist hooks can be readily attached. It is loaded/unloaded into/from the tank by withdrawing the tank's hinged top.

Suggested materials of construction for the decontamination facility are shown in Table 1. For each system component, up to three choices are given in order of decreasing preference. On the basis of the most preferred material for each component, preliminary cost estimates were suggested as follows:

Equipment	\$140,000
Installation	\$170,000
Engineering	\$ 50,000
Total	\$360,000

The estimates appear to be rather low; actual expenditures may be considerably higher due to relatively high overhead costs in Ontario Hydro.

The materials listed in Table 1 formed the basis for the procurement and evaluation of materials for the proposed acid service. Details are given in the next section.

7.0 EXPERIMENTAL EVALUATION OF MATERIALS

Material choices shown in Table 1 arise from the rather demanding requirements for HF/HNO₃ acid service. Since service under the proposed decontamination conditions could be more severe due to the higher temperature than under usual pickling environments, experiments were conducted to evaluate the suitability of the materials suggested by Ledge along with that of other identified candidate materials. Included were several grades of high chromium stainless steels⁸.

⁷ At BNPDS, steam is available at 276 kPa (pressure reliefs provided at 345 and 380 kPa) and 83 kPa (pressure relief at 138 kPa).

⁸ While several metals are suitable for HNO₃ or HF acid service, only high chromium steels can withstand the combined acid attack/11/.

TABLE 1

PROPOSED MATERIALS OF CONSTRUCTION
FOR THE DECONTAMINATION FACILITY

<u>Equipment</u>	<u>Proposed Materials of Construction</u>
Pickle tank	1. carbon steel lined with Kynar and carbon bricks set in HF-resistant Furan cement. 2. FRP/polypropylene
Cover	1. FRP with Nexus veil. 2. carbon steel lined with Kynar.
Rack	1. fibreglass reinforced vinyl ester resin with Nexus veil. 2. carbon fibre reinforced vinyl ester resin. 3. Kynar.
Pump & Fan	1. cast iron lined with Teflon. 2. solid Kynar.
Heat exchanger	1. carbon block with Teflon gaskets and carbon steel shell.
Vessels other than tank	1. carbon steel lined with Kynar. 2. FRP/PVC or FRP/polypropylene.
Piping	1. carbon steel lined with Kynar. 2. carbon steel lined with Teflon.
Ducting	1. FRP/polypropylene. 2. FRP/PVC.

Samples exposures were made in covered Pyrex reaction kettles /3/. They were conducted for extended durations (1-3 weeks) in solutions containing 1 wt% HNO_3 and 0.05% HF at temperatures ranging from 75-95°C. Details including sources of materials and results are given in Appendix 1. Acceptable materials of construction selected on the basis of weight loss measurements and change in appearance, are listed in Table 2 below.

TABLE 2
ACCEPTABLE MATERIALS OF CONSTRUCTION

No*	Material
1	FRP with Nexus veil
6	Teflon
7	Kynar
9	Chlorinated PVC
13	Chlorobutyl rubber
14&17	Carbon bricks set in Carbo-Vitrobond mortar
18-21	High Cr steels
22	Graphite impregnated with Teflon

*See Table A.1 in Appendix 1.

In addition to the above, use of Teflon, Kynar and chlorinated PVC as FRP backed laminates would also be appropriate. Note that the materials listed above include some of the suggestions for preferred materials in Table 1. Exceptions were Carbo-Alkor (carbon filled Furan mortar) which had a relatively high weight loss and imparted a yellowish colouration to the solution and polypropylene which discoloured as a result of exposure.

Besides Furan mortar, Carbo-Vitroplast, a polyester resin-based mortar utilizing a 100% carbon filler, and Carbo-Vitrobond, a 100% carbon-filled plasticized hot pour sulfur-based mortar were also evaluated. Carbo-Vitroplast was judged inadequate for the same reasons as Furan mortar. On the other hand, Carbo-Vitrobond manifested no adverse effects in solution. However, its upper temperature limit is perilously close to the intended service temperature. Therefore, the use of Carbo-Vitrobond is recommended although with caution.

Nitric and hydrofluoric acids have higher boiling points than water. Therefore, materials of construction in the vapour handling system of the proposed facility may experience relatively mild service conditions. To ascertain this, samples of the condensate returning back to the liquid phase in the reaction kettle were collected. Analysis revealed their nitrate and fluoride ion concentrations to be significantly lower (distribution coefficients of 270 and 80, respectively and a condensate pH of ~ 3.0 were measured in one experiment; there was considerable scatter in the measured coefficients, however) than in the liquid phase. Based on this finding, it is suggested that polypropylene or FRP backed polypropylene, although unsuitable for liquid service, would be appropriate ducting materials in the vapour recovery system.

It is worth noting that in ENEL's (Italian State Electricity Board) decontamination test loop/12/ used for evaluating aggressive decontaminants including solutions containing 1.5% HF + 15% HNO₃ at application temperatures ranging from 30 to 90°C, the materials in contact with process reagents are Teflon and Kynar/12/.

Finally, monitoring of nitrate and fluoride ion concentrations in the liquid phase during sample exposures indicated practically no change for durations of up to one week. Besides obviously good condenser performance, this indicates the formation of little, if any, NO_x fumes (the absence of brownish fumes also confirms this). It follows that with a well designed vapour recovery system, provisions for make-up water and acids would be minimal.

8.0 REGENERATION OF DECONTAMINATION SOLUTIONS

A preliminary investigation of ion exchange as a means for regenerating spent decontamination solutions was previously/3/ carried out using the strong acid cation exchanger IRN-77 (Rohm & Haas). The resin effectively removed dissolved metal (cation selectivity decreased in the order Ni, Fe and Cr) from solutions maintained at 95°C indicating that cooling of feed solutions below the temperature of decontamination was not necessary provided resin degradation is minimal. It was also shown that acidity (as wt% HNO₃) could be increased significantly (up to 3%) prior to loss of ion exchange effectiveness.

Amberlite 200 and 252 strong acid resins available also from Rohm & Haas, are claimed to have superior resistance (compared with IRN-77) to resin degradation and physical breakdown under oxidizing and elevated temperature conditions/13,14/. Of the two, Amberlite 200 was selected for evaluation due to its higher degree of cross-linking; the latter imparts an increased temperature resistance which is, however, gained at the expense of capacity. Its total exchange capacity is 1.7 meq/mL although the actual operating capacity, is lower. The resin may be used over the pH range 1 to 14 and at a maximum temperature of 150°C.

A potential explosive hazard exists in the use of nitric acid in ion exchange operations, particularly those involving anion exchangers/14,15/. No accidents related to the use of dilute nitric acid on cation exchange resins have, however, been reported. The principal concern to date has been the effect of nitric acid upon the useful life of the cation exchanger. Despite this record, Rohm & Haas advocate consultation with knowledgeable sources in each specific case.

The plutonium recovery operation at the Savannah River Plant involves exhaustion of strong acid cation exchange resin columns with plutonium contained in dilute HNO₃ streams and its subsequent recovery by column elution with 6 M HNO₃ at 40°C/16/. The

low recovery temperature is dictated by factors other than those concerning resin stability. Discussions regarding the proposed use of cation exchange resins for regenerating the SFSB decontamination solution confirmed that 1% HNO_3 solutions at 95°C could be safely handled. Resin degradation, if any, could be minimized by appropriate sizing of columns. This would limit solution exposure of the resin prior to column exhaustion with the spent resin being subsequently discarded rather than regenerated. It was also suggested that storage of the spent resin in a HNO_3 environment would pose no hazard.

In accordance with the above, a simple calculation of the exposure duration for a column of volume 0.5 m^3 is described below:

Based on a tank volume (V) of 10 m^3 and a purification flow rate (F) of $10 \text{ m}^3/\text{h}$ (a flow rate of 16 bed volumes/h is recommended for Amberlite 200), the purification half-life $t_{1/2}$ is estimated ($t_{1/2} = 0.693 V/F$) to be 0.7 h.

Based on the results in Figure 5 (see later), the operating capacity of the column was assumed to be equal to 5 kg total metal.

The processing of six SFSBs/h/batch/9/ increases the concentration of dissolved metal in solution by 30 ppm. If the purification circuit is operated for 0.7 h at the end of every batch, except the first, the solution concentration would be maintained in the acceptable range of 30 to 60 ppm. Since 300 g metal is exchanged in 0.7 h, at the end of every batch, the resin exposure will span the processing duration of ~ 17 batches ($5 \times 10^3/300$) of which only ~ 12h (17×0.7) is at the elevated temperature.

It is concluded from the foregoing that resin degradation in service would be minimal.

In addition to metal ions, the Amberlite 200 resin will also remove radioactive contamination dissolved in solution. Of the principal contaminants, namely, Cs-137, and Co-60/2/, exchange of monovalent cesium may not be favourable. To assess this and to confirm the expected behaviour of the resin with respect to removal of the dissolved cations, experiments were conducted in which spent HF/HNO_3 solutions prepared by exposure⁹ of SFSB surfaces were ion exchanged using Amberlite 200. A typical composition of the solution is given in Table 3.

⁹ During exposures, no evidence of H_2 was found (by GC) in samples drawn from the vapour space above the liquid. The detection limit was $100 \mu\text{L/L}$.

TABLE 3

COMPOSITION OF SOLUTION ION EXCHANGED USING AMBERLITE 200

HNO ₃	1 wt%
HF	0.05 wt%
Fe	189 ppm
Cr	50 ppm
Ni	29 ppm
Cs-137	0.23 nCi/mL
Co-60	0.06 nCi/mL

Figure 5 shows the typical behaviour of Fe and Cr in the column effluent. The results are for a solution that was specifically prepared in polyethylene containers to exclude Si, Na, Al, B and Ca contamination¹⁰ which are introduced into solution if glassware is used. Note the initial sharp increase in Cr to a relatively constant effluent concentration is followed by another rapid increase just prior to the Fe breakthrough. In contrast, Ni was below detection limits throughout. Further, Co-60 and significantly Cs-137 were both effectively exchanged with no measurable activity in the effluent. Similar results were obtained when solutions at 95°C were processed.

The selectivity coefficients for a styrene-divinylbenzene (8%) sulfonated copolymer (such as IRN-77), relative to a value of unity for Li⁺, have been reported/17,18/ as Ni²⁺(3.93) > Co²⁺(3.74) > Fe²⁺ > Cs⁺(3.25). With a higher degree of crosslinking (16% divinylbenzene), the coefficients were 4.06, 3.81 and 4.66 for Ni²⁺, Co²⁺ and Cs⁺, respectively (no data given for Fe²⁺)/18/. Note the increase with degree of crosslinking, in particular, for the selectivity coefficient of Cs⁺. At least among Ni²⁺ and Co²⁺ ions and possibly Fe²⁺ ions as well, the exchange of Cs⁺ ions becomes the most favoured. The experimental findings with regard to the exchange behaviour of the above cations on Amberlite 200 (a styrene 20% divinylbenzene sulfonated copolymer) in the present study is in keeping with the reported selectivity coefficients data.

¹⁰ As it turned out, the presence of the contaminants had no effect on the ion exchange behaviour of the principal species in solution.

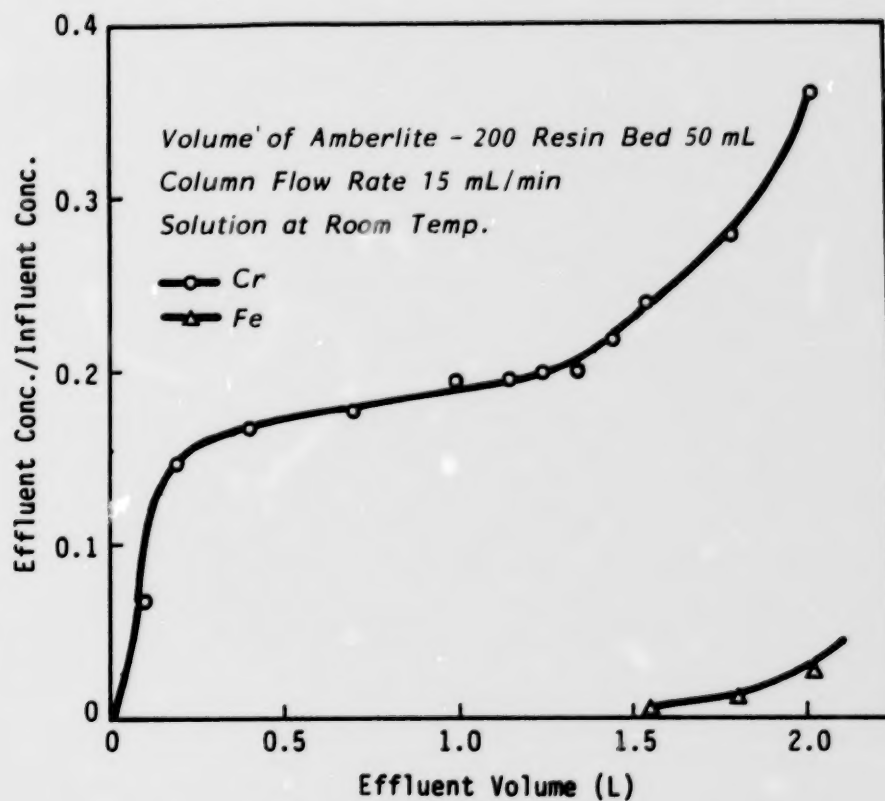


FIGURE 5
BEHAVIOUR OF IRON AND CHROMIUM DURING ION-EXCHANGE
OF SPENT SFSB DECONTAMINATION SOLUTION

Chromium leakage during the present studies was also observed previously using IRN-77/3/. The unusual behaviour of chromium with effluent volume may lead to unacceptably high chromium levels after repeated processing of the tank solution. It merits further investigation.

On the basis of Figure 5, a resin capacity equal to -9 kg total metal per m^3 resin can be estimated corresponding to the breakthrough point for Fe. This represents about 20% (assuming the principal cationic species to be Fe^{+2}) of the resin's total exchange capacity. In practice, a column may possibly be operated up to much higher loading before the increased metal leakage becomes unacceptable.

9.0 DISPOSAL OF DECONTAMINATION SOLUTION

When all SFSBs and associated structures have been decontaminated, approximately 3000 gallons of dilute acid solution would remain. Direct release of this solution into the lake is subject to the limitations specified in Table 4 below. Due to provisions for metal removal in the proposed flow sheet, the concentration of

TABLE 4

RELEASE LIMITS FOR RELEVANT ACIDS AND METALS/19/

<u>Species</u>	<u>Release Limit</u>
Nitrate	10 mg/L
Fluoride	2.4 mg/L
Fe	300 $\mu\text{g/L}$
Cr	100 $\mu\text{g/L}$
Ni	25 $\mu\text{g/L}$

dissolved metals can possibly be reduced below their release limits. However, the concentrations of nitrate and fluoride ions in solution would considerably exceed their release limits. The solution, therefore, would require treatment to reduce its acid content to acceptable levels prior to discharge.

The simplest option, provided the acid solution is not radioactive, is to contract out its treatment and eventual disposal. Otherwise, means for reducing its nitrate and fluoride levels must be sought for acceptance of the treated solution by a licensed Radioactive Liquid Waste Management System¹¹ (RLWMS)/20/.

¹¹ BNPDS does not have a RLWMS. Such a facility, however, exists at BNGS.

Consider briefly the alternatives for treating metal loaded waste pickle liquors/6,21/ namely,

- 1) Neutralization with lime - in practice, the treated liquor is processed through a filter press to remove insoluble metal hydroxides and calcium fluoride (for disposal at a landfill) while the filtered solution containing dissolved nitrates is diluted with other waste streams for release.
- 2) Acid recovery by partial evaporation and cooling - the acid is partly recovered in the condensate during the evaporation step, partly from thermal decomposition of the metal fluoride crystals formed in the subsequent cooling step and the remaining in the filtered concentrate, and
- 3) Acid recovery by acid sorption as in Eco-Tec's process.

Since neutralization with lime does not reduce the nitrate content of the effluent, it is not a feasible method for processing the decontamination waste solution. The other two alternatives, although feasible, entail significant additional capital expenditures not justifiable for a once-only disposal occurrence. Considering the dilute nature of the waste solution and provisions for ion exchange in the proposed system, the use of weak and/or strong base anion resins offer a simple means ($\sim 3\text{m}^3$ resin would be required) for acid removal from the solution.

The relatively high capacity of weak base resins is offset by their inability to effectively remove weak acids from solution/22/. Fluoride ions in solution would, therefore, not be exchanged. Strong base resins although having lower capacity would, however, effectively remove both nitrate and fluoride ions from solution. An appropriate strong base resin available from Rohm & Haas for processing the decontamination waste solution is IRA 400/23/.

Due to explosion hazards associated with storage of anion exchange resins in the nitrate form/14,15/, it is recommended that following waste solution processing, the resin be converted to the sulphate or hydroxide form/16/. The inactive nitrate effluent resulting from this step along with the inactive spent resin could be disposed of by conventional means. All other effluents arising from the processing of the waste solution could be routed to the RLWMS.

10.0 CONCLUSIONS AND RECOMMENDATIONS

Decontamination of SFSBs and associated structures to release limits using a dilute solution of nitric and hydrofluoric acids is technically feasible. Because the process is regenerative, the

associated waste management is limited to the disposal or storage of spent ion exchange resin. Assessment of the radiation fields due to a spent resin column (see Appendix 2) suggests that the man-rem associated with performing the decontamination would be very modest.

The economics of the process hinges on the effective removal from solution of dissolved metals, both active and inactive. For this reason, it would be advisable to explore further, preferably on a larger scale, the regeneration of the decontamination solution and its final disposal.

Completion of the present study sets the stage for an economic comparison between the two options for treatment of the SFSBs, namely 1) decontamination to release limits and 2) compaction followed by storage. The end result in the first option is the concentration of radioactivity present on the SFSB surfaces onto ~ 15 m³ ion exchange resin while in the second case a compacted radioactive waste volume exceeding 100 m³ would be obtained¹². It is strongly recommended that a comparison between the two options should also consider the benefits of developing an in-house capability to effect large scale decommissioning-type decontaminations of metallic wastes in general. It is pertinent to mention here that there is considerable interest world-wide in decontamination-for-release technology/25-28/. For instance, DOE/25/ is initiating a program to decontaminate and process a large quantity of radioactively contaminated metallic scrap and prepare it for beneficial reuse.

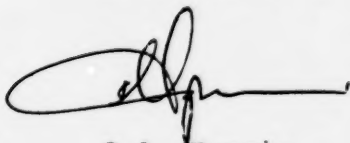
Should decontamination of the SFSBs to release limits be the favoured option, it is recommended that the detailed engineering and construction of the decontamination facility should involve the participation of metal finishing consultants and draw upon the expertise in the stainless steel pickling industry.

¹² A volume reduction factor of 10 may be achieved by compaction. This is based on results obtained in a SFSB compaction test using a 275 ton compactor/24/.

ACKNOWLEDGEMENTS

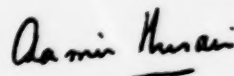
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APPENDIX 1

EXPERIMENTAL EVALUATION OF MATERIALS

Table A.1 is a list of materials evaluated for their reagent compatibility. With the exception of MONIT (Material #19) and Graphilor TH (#22) which were supplied as tubular sections and Carbo-Vitroplast (#16) as short cylinders, the remaining materials were supplied as flat sections. Coupons were prepared from these except in the case of Materials #1-4. These were supplied with their edges sealed to prevent acid attack on the veil or fibres within, and were used without further sectioning.

Exposures were made in covered Pyrex reaction kettles/3/ for durations of 1 to 3 weeks. The solutions containing 1% HNO_3 and 0.05% HF were applied at 75-95°C. Exposure history and the resulting weight loss and appearance of each material are documented in Table A.2. Due to absorption of solution, weight loss for the non-metallics was determined after extended baking in an oven. Despite this, moisture removal was incomplete as evident from an overall weight gain for some materials.

Based on the results in Table A.2, it was concluded that

- 1) although no preferred choice was evident among candidate Materials #1-4 (construction materials for the pickle tank cover and rack), Material #1 is selected based on the supplier's recommendation and the material's upper temperature limit,
- 2) Teflon (#6), Kynar (#7) and chlorinated PVC (#9) displayed outstanding resistance,
- 3) carbon bricks (#14) set in Carbo-Vitrobond mortar (#17) are acceptable tank lining materials,
- 4) Teflon impregnated graphite (#22) is acceptable as a heat exchanger tube material, and
- 5) all the stainless steels (#18-21) examined have adequate corrosion resistance with that for 904 L (#18) being lower than for the other steels; their corrosion rate of less than 10^{-2} $\mu\text{m/h}$ is substantially lower than the expected 1 $\mu\text{m/h}$ metal removal rate from SFSBs surfaces.

TABLE A.1
MATERIALS SELECTED FOR EVALUATION

No	Material	Supplier	Material Designation
1	Silica reinforced polyester with Nexus veil, Ta up to 400°F	Alcore Fabricating	FRP-D-2-N
2	As in 1, Ta up to 200°F	"	FRP-D-1-N
3	FRP, carbon reinforced	"	FRP-C-D-1
4	FRP with carbon veil, Ta higher than for #3	"	FRP-C-D-2
5	Teflon, glass reinforced, Ta 400°F	"	TFE-C-J
6	Teflon, Ta 450°F	"	TFE-V-J
7	Kynar, Ta 250°F	"	PVDF-K-W
8	Chlorinated PVC, Ta 220°F	"	CPVC-4-E-B
9	Chlorinated PVC	"	CPVC-4-C-T
10	Polypropylene, Ta 180°F	"	PPSR-E-T-1
11	PVC, Ta 160°F	"	PVC-1-E-T-1
12	PVC, Ta 160°F	"	PVC-1-C-D-5
13	Chlorobutyl rubber	Snowden Rubber	BUT60-4
14	Carbon brick	Alphatherm	-
15	Carbo-Alkor	H.L. Blachford	-
16	Carbo-Vitroplast	"	-
17	Carbo-Vitrobond	"	-
18	SS (Cr 20, Ni 25, Mo 4.5, Cu tr)	Avesta Stainless	904 L
19	SS (Cr 25, Ni 4, Mo 4, Ti tr)	"	MONIT
20	SS (Cr 25, Ni 20)	"	25 L
21	SS (Cr 25, Ni 22, Mo 2, N tr)	"	725 LN
22	Teflon impregnated graphite	Carbone Lorraine	Graphilor TH

Notes: 1) Ta, upper temperature limit; 2) tr, trace.

TABLE A.2
RESULTS OF MATERIALS EVALUATION

Material No	Exposure History	Weight Loss	Appearance
1	See note 1 184 h (95°C)	-ve -ve	uc uc
2	See note 1	Neg	uc
3	See note 1	0.06%	uc
4	See note 1	-ve	uc
5	See note 2	0.95%	uc
6	See note 2	Neg	uc
7	See note 2 184 h (95°C)	Neg Neg	uc uc
8	See note 2	Neg	disc
9	See note 2 184 h (95°C)	Neg Neg	uc uc
10,11	See note 2	Neg	disc
12	See note 2	0.12%	disc
13	See note 1 188 h (95°C)	-ve -ve	uc uc
14	184 h (95°C)	Neg	uc
15	184 h (95°C)	2.4%	See note 3
16	188 h (95°C)	0.45%	See note 3
17	149 h (95°C)	0.40%	uc
18	104 h (95°C) 184 h (95°C)	6.8 10^{-3} mg/cm ² /h 6.0 10^{-3} mg/cm ² /h	uc uc
19	184 h (95°C)	1.2 10^{-3} mg/cm ² /h	uc
20	184 h (95°C)	0.9 10^{-3} mg/cm ² /h	uc
21	184 h (95°C)	1.1 10^{-3} mg/cm ² /h	uc
22	See note 2 184 h (95°C)	0.15% 0.12%	uc uc

uc, unchanged; disc, discoloured; neg, negligible

NOTES

- 1) 168 h (75°C) + 164 h (85°C) + 151 h (95°C)
- 2) 143 h (75°C) + 211 h (85°C) + 163 h (95°C)
- 3) Samples unchanged in appearance, although solution turned yellow.

APPENDIX 2

ESTIMATION OF RADIATION DOSE FROM LOADED ION EXCHANGE COLUMN

In accordance with the proposed flow sheet for the SFSB decontamination (Figure 4), the activity released into the pickle tank solution is subsequently concentrated on the ion exchange resin bed. The fully loaded bed, therefore, represents the largest source of radiation dose in the system. Estimates are given below for the maximum radiation doses expected on contact with the ion exchange column and at 1 m from it.

Consider a column of volume 0.2 m^3 , length 1.32 m, diameter 0.44 m (ie, a typical L/D ratio of 3) and thickness of column wall 3 mm. The following assumptions are made to determine an upper bound to expected radiation fields:

- 1) The total exchange capacity of the resin bed is realizable, ie, 1.7 eq/L.
- 2) Activity in solution, although principally due to Cs-137, is assumed to be entirely due to Co-60 with its associated higher energy emissions.
- 3) The mass absorption coefficient for the resin-water system is assumed equal to $0.055 \text{ cm}^2/\text{g}$ which corresponds to the value for oxygen and carbon at 1.25 MeV (this represents the average of 100% gamma emissions at 1.17 and 1.33 MeV for Co-60)/22/. Values for H and H_2O are higher. Since the density of the resin material is 1.3 g/cc and resin bed voidage 40%/13/ it follows that the linear absorption coefficient equals 0.065 cm^{-1} ($0.055 \times [1.3 \times 0.6 + 1.0 \times 0.4]$).

Column activity is associated with its metal loading. The metal (as Fe^{+2}) exchange capacity of the column is 10^4 g ($1.7 \times 10^3 \times 0.2 \times 59/2$) or 1250 cm^3 . This quantity is equivalent to the removal of a $1 \text{ }\mu\text{m}$ layer from 1250 m^2 of SFSB surface. Since the maximum SFSB surface contamination is $30 \text{ }\mu\text{Ci}/\text{m}^2/2/$, the total activity associated with the metal on the column is therefore $3.75 \times 10^4 \text{ }\mu\text{Ci}$. This is equivalent to a source density of $13.9 \times 10^3 \text{ photons}/\text{cm}^3\text{s}$ ($3.75 \times 10^4 \times 3.7 \times 10^4 \times 2/0.2/10^6$) with an average energy of 1.25 MeV.

The procedure for calculating the radiation dose due to a uniformly distributed cylindrical source has been described by Rockwell/29/. Based on the above data, a build-up factor of unity and a cylindrical column of infinite length, the radiation fluxes on contact and 1 m from the column surface were calculated to be

6×10^4 and 7×10^3 photons/cm²s. The corresponding fields (for 1.25 MeV photons, $1 \text{ MeV/cm}^2\text{s} \equiv 1.85 \times 10^{-6} \text{ R/h}$) are 139 and 16 mR/h, respectively.

The calculations outlined above were repeated assuming Cs-137 as the sole contributor to activity in solution. Expectedly, the fields were lower - 22 mR/h on contact and 3 mR/h 1 m from the column surface.

Due to the conservative assumptions made in the above calculations, fields in practice can be expected to be significantly lower. Shielding requirements for the column and by inference for the pickle tank and associated systems are, therefore, considered to be very modest.

REFERENCES

1. Sinclair, A., "Regulatory Approval for Sale of Obsolete Fuel Trays", Memo to Goodwin, S.R. (Jan 28, 1982).
2. Husain, A., "Surface Characterization of Pickering NGS 'A' Spent Fuel Storage Basket", Ontario Hydro Research Division Report 84-370-H.
3. Husain, A., "Decontamination of Pickering NGS 'A' Spent Fuel Storage Baskets - Reagent Development", Ontario Hydro Research Division Report 85-278-H.
4. Covino, B.S. et al, "Dissolution Behaviour of 304 Stainless Steel in HNO_3/HF Mixtures", Metallurgical Trans A 17A, 137 (1986).
5. Private communication with Zaremski, D., Allegheny Ludlum Steel Company, Brackenridge, Pennsylvania.
6. Visit to Eco-Tec, Pickering, Ontario arranged with Dejak, M.
7. Private communication with Pinnow, K., Crucible Research Centre, Pittsburg, Pennsylvania.
8. Visit to Atlas Stainless Steels, Tracy, Quebec arranged with Godin, R. and Paquette, A.
9. Preliminary estimate of SFSB decontamination project cost by Spooner, P.
10. "Metal Finishing", Metal and Plastics Publications, Inc, New Jersey (1985).
11. Fontana, M.G., and Green, N.D., "Corrosion Engineering", 2nd Edition, McGraw-Hill Inc. (1978).
12. Pascali, R., Bregani, F., Ronchetti, C., and Rizzi, R., "Hard Chemical Decontamination of Parts of the Primary Loop of Serviced Nuclear Plants", Water Chemistry of Nuclear Reactor Systems 3, Vol. 1, BNES, London (1983).
13. "Amberlite 200", Technical Bulletin from Rohm & Haas Co., Philadelphia, Pennsylvania (July 1980).
14. "A Note of Caution on the Use of Nitric Acid with Ion Exchange Resins", Published by Rohm & Haas Co, Philadelphia, Pennsylvania (May 1976).

15. Calmon, C., "Explosion Hazards of Using Nitric Acid in Ion Exchange Equipment", Chemical Engineering 87(23), 271 (November 17, 1980).
16. Private communication with Burney, G., Savannah River Plant, Aiken, S. Carolina.
17. Calmon, C., 'The Ion Exchange Process', in Ion Exchange For Pollution Control, Volume 1. Edited by Calmon, C., and Gold, H., CRC Press, Inc., Florida (1979).
18. Helfferich, F., Ion Exchange, p 169, McGraw - Hill, Toronto (1962).
19. "Water Management: Goals, Policies, Objectives, and Implementation Procedures" Ministry of Environment (May 1984).
20. Private Communication With Moulton, P.G., Radioactivity Management and Environmental Protection Department (September 2, 1986).
21. Krepler, A., "Total Regeneration of the Waste Pickle Liquor for Stainless Steel", Technical Report Published by Ruthner Industrieanlagen Aktiengesellschaft, Vienna.
22. "Amberlite IRA-93", Technical Bulletin, Rohm & Haas Co., Philadelphia, Pennsylvania (May 1978).
23. "Amberlite IRA-400", Technical Bulletin, Rohm & Haas Co., Philadelphia, Pennsylvania (September 1984).
24. McKerlie, C., "Demonstration - Dempster Balestar 275 tons", Memo to File WI-79300 (T-5) (June 4, 1986).
25. "DOE Initiating Scrap Processing Program", Nuclear News, p 77 (April 1986).
26. "Cleaning Up Scrap", Nuclear Engineering International, p 7 (January 1986).
27. Agostinelli, A., Bregani, F., Pascali, R., & Ronchetti, C., "Vigorous Decontamination Tests of Steel Samples", Proceedings of the 1982 International Decommissioning Symposium, Seattle, Washington (October 10-14).
28. Pascali, R., Bregani, F., Ronchetti, C., and Rizzi, R., "Hard Chemical Decontamination of Parts of the Primary Loop of Serviced Nuclear Plants", Water Chemistry of Nuclear Reactor Systems 3, Vol. 1, BNES, London (1983).
29. Rockwell, T., "Reactor Shielding Design Manual", 1st Edition, USAEC, TLD-7004 (March 1956).

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